The kinetics and mechanisms of gas phase elimination of the ethyl ester of amino acid hydrochlorides

Gabriel Chuchani,* Armando Herize, Rosa María Domínguez, Alexandra Rotinov and Maria Tosta

Centro de Química, Instituto Venezolano de Investigaciones Científicas (I.V.I.C.), Apartado 21827, Caracas 1020-A, Venezuela

ABSTRACT: The kinetics of the gas phase elimination of the ethyl ester of four α-amino acid hydrochlorides have been examined over the temperature range of 339–451°C and pressure range of 8–108 Torr. The reactions, in a static reaction system, are homogeneous, unimolecular, and follow a first-order rate law. The rate coefficient is expressed by the following Arrhenius equations:
Glycine ethyl ester hydrochloride:

$$\log\ k_1(\sec^{-1}) = (12.29 \pm 0.24) - (203.7 \pm 3.2)\,\text{kJ mol}^{-1}\,(2.303\ RT)^{-1}$$

Sarcosine ethyl ester hydrochloride:

$$\log\ k_1(\sec^{-1}) = (13.64 \pm 0.60) - (215.0 \pm 7.8)\,\text{kJ mol}^{-1}\,(2.303\ RT)^{-1}$$

DL-Alanine ethyl ester hydrochloride:

$$\log\ k_1(\sec^{-1}) = (12.49 \pm 0.46) - (200.2 \pm 5.9)\,\text{kJ mol}^{-1}\,(2.303\ RT)$$

L-Phenylalanine ethyl ester hydrochloride

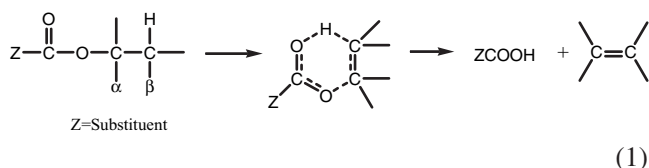$$\log\ k_1(\sec^{-1}) = (12.49 \pm 0.09) - (194.4. \pm 1.1)\,\text{kJ mol}^{-1}\,(2.303\ RT)^{-1}$$

The elimination of these amino ester hydrochlorides leads to the formation of the corresponding α-amino acid and ethylene. However, the amino acid intermediates, except sarcosine, under the condition of reaction temperatures, undergo an extremely rapid decarboxylation process. These results apparently support previous reported mechanistic consideration where α-amino acids decompose to the corresponding amines and CO_2 gas. Copyright © 2006 John Wiley & Sons, Ltd.

KEYWORDS: elimination; gas-phase kinetics; mechanism; ethyl glycine hydrochloride; ethyl sarcosine hydrochloride; ethyl DL-alanine; ethyl L-phenyl alanine hydrochloride

INTRODUCTION

The homogeneous unimolecular gas phase eliminations of ester of carboxylic acids are generally known to proceed through a six-membered cyclic transition state type of mechanism to yield the corresponding carboxylic acid and the olefin, respectively [reaction (1)][1,2]. For molecular elimination, the presence of a C_β—H bond at the alkyl side of the ester is necessary .

$$Z=\text{Substituent} \tag{1}$$

The acid product of these esters with a substituent at the α-position, under the reaction conditions, may further decompose into another products. In this respect, the gas phase elimination of several types of 2-substituted carboxylic acids[3–9] have been described, both experimentally and theoretically, in terms of a decarbonylation process as depicted in reaction (2).
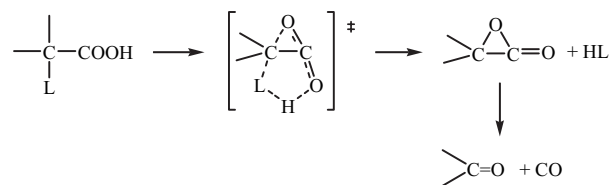
L = Leaving Group: Cl, Br, OH, OR, OPh, OAc.

$$\tag{2}$$

However, 2-substituted amino carboxylic acids proceed a decarboxylation process as reported in the

*Correspondence to: Prof. G. Chuchani, Centro de Química, Instituto Venezolano de Investigaciones Científicas (I.V.I.C.), Apartado 21827, Caracas 1020-A, Venezuela.
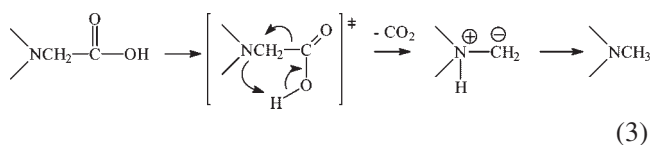E-mail: chuchani@ivic.ve

homogeneous, unimolecular gas phase pyrolysis of N,N-dimethylglycine,[10] picolinic acid,[11] and N-phenylglycine[12] [reaction (3)].

$$(3)$$

The above-mentioned substrates[10–12] have been found to be very reactive species in the gas phase. The fact that neutral α-amino acids decompose rapidly in the gas phase is supported from the experimental results on the elimination kinetics of the said compounds when compared as intermediate products of their corresponding ethyl ester pyrolysis. However, the gas-phase pyrolysis of 2-(N-phenylamino)propanoic acid[13] was thought to decarbonylate through a five-membered cyclic transition state type of mechanism similar to reaction (2). Consequently, this result differs from the decarboxylation process of the α-amino acids described in reaction (3). Moreover, the pyrolysis products of 2-(N-arylamino)propanoic acids[13] were found to yield $ArNH_2$, CH_3CHO, and CO, which appears to justify reaction (2).

Recently, the elimination kinetics of ethyl esters of pipecolinic and N-methylpipecolinic acids[14] in the gas phase indicated the formation of the corresponding carboxylic acids and ethylene. The acid intermediate with the N atom at the α-position of the carboxylic acid, an amino acid derivative, proceeds to a very rapid decarboxylation process as described in reaction (3). This work apparently supports the elimination of neutral α-amino acids through a five-membered cyclic transition state to produce the corresponding substituted amine and CO_2 gas.
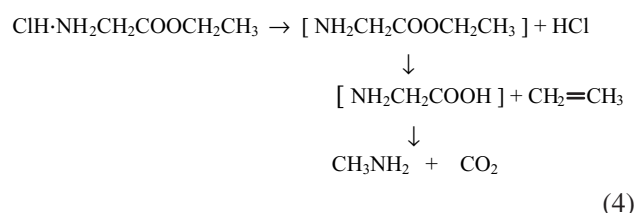
Because of different products formation of the 2-amino acids[12,13] as described in reaction (2) with those substrates [9–11,14] undergoing a process as in reaction (3), the present work aimed at determining the kinetic and thermodynamic parameters of the gas phase elimination of α-amino acids intermediates through a consecutive reaction from the corresponding ethyl ester hydrochloride decomposition. The amino ester hydrochlorides were chosen by virtue that NH_4Cl decomposes at high temperatures into NH_3 and HCl. Under such condition, the NH_4Cl is attributed to be a strong acid. In this respect, this investigation thought as a challenge to examine if the aminoester hydrochloride salts may decompose, at high temperature, into the corresponding free ester and HCl. Consequently, the ester may then proceed to pyrolytic elimination as reported. This mode of experimental approach was applied because most α-amino acids of low molecular weight are solids and difficult to determine their elimination kinetics in the gas phase. These compounds on heating sinter or decompose into a vitreous materials, and unfortunately are insoluble in most organic solvents. Their high solubility in water,

forming zwitterions species, limits their examination as neutral molecules in the gas phase. Consequently, the objective of this work is to investigate on how the nitrogen atom at the α-position of the carboxylic acid intermediates would affect the elimination process. Therefore, the substrate for this investigation are the ethyl ester hydrochlorides of glycine, sarcosine, DL-alanine, and L-phenylalanine.

RESULTS AND DISCUSSION

Glycine ethyl ester hydrochloride

The molecular gas phase pyrolytic elimination of this substrate proceeds according to reaction (4).

$$ClH \cdot NH_2CH_2COOCH_2CH_3 \rightarrow [\, NH_2CH_2COOCH_2CH_3 \,] + HCl$$
$$\downarrow$$
$$[\, NH_2CH_2COOH \,] + CH_2{=}CH_3$$
$$\downarrow$$
$$CH_3NH_2 \; + \; CO_2$$

$$(4)$$

The stoichiometry of reaction (4) requires that for long reaction time the final pressure should be four times the initial pressure, that is, $P_f/P_0 = 4$. The average experimental results at 4 different temperatures and 10 half-lives is 3.9 (Table 1). To check stoichiometry (4), up to 50% reaction, was possible by comparing the pressure measurements with the quantitative chromatographic analysis of ethylene gas (Table 2).

The effect of the surface on the rate of elimination was examined by carrying out several runs in a vessel with a surface-to-volume ratio of 6.0 relative to that of the normal vessel, which is equal to 1.0 (Table 3). Packed and unpacked Pyrex vessel seasoned with allyl bromide and the unpacked clean Pyrex Vessel showed no effect on the reaction rates. However, the packed clean Pyrex vessel had a small heterogeneous effect. The addition of different proportion of the free radical inhibitor propene exhibited no effect on rates (Table 4). Moreover, no induction period was observed.

The first order rate coefficient for elimination of this substrate showed no significant variation change of the initial pressure (Table 5) and the first order plots of log $(4P_0 - P)$ against time t are linear up to 50% reaction.

Further decomposition leads to a relative standard deviation greater than $\pm 5\%$. The rate equation of four-product formation by pressure increase is described as follows:
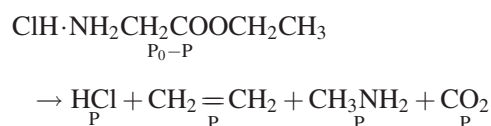
$$\underset{P_0-P}{ClH \cdot NH_2CH_2COOCH_2CH_3}$$

$$\rightarrow \underset{P}{HCl} + \underset{P}{CH_2{=}CH_2} + \underset{P}{CH_3NH_2} + \underset{P}{CO_2}$$

Table 1. Ratio of final (P_f) to initial (P_0)

Substrate	Temperature (°C)	P_0 (Torr)	P_f (Torr)	P_f/P_0	Average
Glycine ethyl ester·HCl	410.0	40	153	3.8	3.9
	420.5	67.5	264	3.9	
	430.7	65	258	4.0	
	440.5	46	177	3.9	
Sarcosine ethyl ester·HCl	399.6	22	71	3.2	3.3
	410.8	40	130.5	3.3	
	420.2	23.5	74.5	3.2	
	430.2	31.5	105	3.3	
DL-Alanine ethyl ester·HCl	379.3	18.6	70.7	3.8	4.0
	390.1	18.9	71.4	3.8	
	400.5	18.5	78.0	4.2	
	409.8	19.5	78.5	4.0	
L-Phenylalanine ethyl ester·HCl	359.5	26.1	100.3	3.8	3.8
	370.0	19.5	74.3	3.8	
	380.0	15.8	61.3	3.9	
	389.6	36.6	138.8	3.8	
	399.6	31.8	122.7	3.9	

Table 2. Stoichiometry of the reaction

Substrate	Temperature (°C)	Parameters	Value				
Glycine ethyl ester·HCl	430.7	Time (min)	1.5	3	5	8	
		Reaction (%) (pressure)	11.3	25.0	38.0	48.1	
		Ethylene (%) (GLC)	12.0	28.4	41.5	53.1	
Sarcosine ethyl ester·HCl	389.1	Time (min)	10	15	21	30	
		Reaction (%) (pressure)	25.3	32.8	46.4	56.8	
		Ethylene (%) (GLC)	23.2	27.1	41.2	53.8	
DL-Alanine ethyl ester·HCl	399.5	Time (min)	6	8	10	12	15
		Reaction (%) (pressure)	25.9	33.5	37.7	42.7	48.6
		Ethylene (%) (GLC)	23.4	32.5	36.7	43.8	54.6
L-Phenylalanine ethyl ester·HCl	389.9	Time (min)	3	6	9	12	18
		Reaction (%) (pressure)	24.9	39.2	44.8	59.8	62.7
		Ethylene (%) (GLC)	28.5	42.7	47.7	61.5	65.0

Table 3. Homogeneity of the elimination reaction

Substrate	S/V (cm^{-1})[a]	$10^4 k_1$ (sec^{-1})[b]	$10^4 k_1$ (sec^{-1})[c]
Glycine ethyl ester·HCl at 420.5°C	1	8.45	8.26
	6	9.13	8.37
2-Sarcosice ethyl ester·HCl at 401.4°C	1	10.81	11.13
	6	21.12[d]	21.76[d]
DL-Alanine ethyl ester·HCl at 400. 5°C	1	8.07	7.95
	6	8.14	8.10
L-Phenylalanine ethyl ester·HCl at 390.0°C	1	14.23	13.99
	6	13.81	13.96

[a] S = surface area; V = volume.
[b] Clean Pyrex vessel.
[c] Vessel seasoned with the products decomposition of allyl bromide.
[d] Average k-values

Table 4. Effect of the free radical chain inhibitor on rates

Substrate	Temperature (°C)	$P_s{}^a$ (Torr)	$P_i{}^b$ (Torr)	P_i/P_s	$10^4 k_1$ (sec^{-1})
Glycine ethyl ester·HCl[c]	430.7	85	—	—	14.17
		96	78	0.8	14.80
		55	91	1.7	14.50
		32	151	4.7	14.28
Sarcosine ethyl ester·HCl[d]	410.8	23	—	—	17.81
		45	42	0.9	17.94
		40	95.5	2.4	18.41
		36.5	140.5	3.9	18.46
		28.5	183	6.4	18.25
DL-Alanine ethyl ester·HCl[d]	400.5	21.5	—	—	7.93
		18.7	40	2.1	8.02
		15.5	90.5	5.8	8.27
		18.5	125.5	6.8	8.04
L-Phenylalanine ethyl ester·HCl[d]	389.6	38.1	—	—	15.65
		37.9	58.0	1.5	14.33
		43.0	89.5	2.1	14.25
		34.3	110.5	3.2	14.67
		35.9	146.5	4.1	14.21

[a] P_s = Pressure of substrate.
[b] P_i = Pressure of free radical inhibitor.
[c] Propene inhibitor.
[d] Toluene inhibitor.

Table 5. Invariability of the rate coefficients from initial pressure

Substrate	Temperature(°C)	Parameters	Value				
Glycine ethyl ester·HCl	430.7	P_0 (Torr)	35.5	55	96	108	
		$10^4 k_1$ (sec^{-1})	14.14	14.50	14.00	14.06	
Sarcosine ethyl ester·HCl	410.8	P_0 (Torr)	28.5	31	40	45	55
		$10^4 k_1$ (sec^{-1})	18.25	18.03	18.41	17.94	18.21
DL-Alanine ethyl ester·HCl	400.5	P_0 (Torr)	8.6	15.5	21.5	25.2	
		$10^4 k_1$ (sec^{-1})	8.09	8.27	8.04	8.02	
L-Phenylalanine ethyl ester·HCl	389.6	P_0 (Torr)	22.0	34.3	43.0	50.7	
		$10^4 k_1$ (sec^{-1})	14.33	14.17	14.25	14.03	

where P_0 = the initial pressure of the substrate P = amount reacted of substrate or formed product then pressure at time t,

$$P_t = P_0 - P + P + P + P + P = P_0 + 3P$$

therefore,

$$P = (P_t - P_0)/3$$

for unimolecular process

$$k = -1/t \ln C/C_0$$

C_0 = initial concentration and C = concentration at time t if

$$C_0 = P_0 \quad \text{and} \quad C = P_0 - P$$

then

$$C = P_0 - [(P_t - P_0)/3] \quad \text{or} \quad C = (3P_0 - P_t + P_0)/3$$

$$C = (4P_0 - P_t)/3$$

consequently $k = -1/t \ln (4 P_0 - P_t)/3 P_0$ or $k = -2.303/t$ log $[(4 P_0 - P_t)/3 P_0]$

The temperature dependence of the rate coefficient and the corresponding Arrhenius equation is given in Table 6 (90% confidence coefficient from least square procedure).

Sarcosine ethyl ester hydrochloride

The products formation from the elimination of sarcosine ethyl ester hydrochloride described in reaction (5) suggest a threefold increase in the final pressure P_f, that is, $P_f/$

Table 6. The variation of the rate coefficients with temperatures

Glycine ethyl ester.HCl	Temp. (°C)	390.7	400.3	410.0	420.5	430.7	440.4	451.0
	$10^4 k_1$ (sec^{-1})	1.78	3.18	5.35	8.45	14.17	23.40	40.93
	Rate equation $\log k_1$ (sec^{-1}) = $(12.29 \pm 0.24) - (203.7 \pm 3.2)$kJ mol^{-1} $(2.303\,RT)^{-1}$, $r = 0.9994$							
Sarcosine ethyl ester.HCl	Temp. (°C)	389.1	399.6	410.8	420.2	430.2		
	$10^4 k_1$ (sec^{-1})	4.75	8.42	18.08	27.96	44.57		
	Rate equation $\log k_1$ (sec^{-1}) = $(13.64 \pm 0.60) - (215.0 \pm 7.8)$kJ mol^{-1} $(2.303\,RT)^{-1}$, $r = 0.9974$							
DL-Alanine ethyl ester.HCl	Temp. (°C)	379.3	390.8	400.5	409.4	420.0	430.5	
	$10^4 k_1$ (sec^{-1})	2.73	4.87	8.07	13.59	23.17	39.38	
	Rate equation $\log k_1$ (sec^{-1}) = $(12.49 \pm 0.46) - (200.2 \pm 5.9)$kJ mol^{-1} $(2.303\,RT)^{-1}$, $r = 0.9996$							
L-Phenylalanine ethyl ester.HCl	Temp. (°C)	339.6	350.4	359.5	370.0	380.0	389.6	399.6
	$10^4 k_1$ (sec^{-1})	0.78	1.55	2.69	4.90	8.51	14.13	23.99
	Rate equation $\log k_1$ (sec^{-1}) = $(12.49 \pm 0.09) - (194.4 \pm 1.1)$kJ mol^{-1} $(2.303\,RT)^{-1}$, $r = 0.9999$							

$P_0 = 3.0$. The average experimental result of P_f/P_0 at 4 different temperatures and 10 half-lives is 3.3 (Table 1).

$$ClH \cdot CH_3 NHCH_2 COOCH_2 CH_3 \rightarrow$$
$$CH_3 NHCH_2 COOH + HCl + CH_2 {=} CH_2 \quad (5)$$
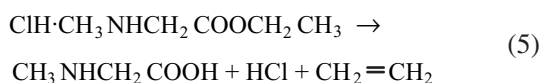
The small departure from the theoretical stoichiometry was due to the formation of a small amount of CO_2 gas. Verification of stoichiometry (5), up to 60% reaction, was performed by comparing the pressure measurements with the quantitative chromatographic analysis of ethylene gas (Table 2). The homogeneity of reaction (5) was examined by using a vessel with a surface-to-volume ratio six times greater than that of the unpacked vessel. The clean packed and unpacked Pyrex vessel has a significant effect on rates (Table 3). However, the packed and unpacked Pyrex vessel seasoned with allyl bromide had no effect on the rate coefficients (Table 3). The effect of the free radical inhibitor toluene is described in Table 4. No induction period was obtained. The rate coefficients are reproducible with a relative standard deviation not greater than ±5% at a given temperature.

The first order rate coefficients of this substrate, calculated from $k = (2.303/t) \log [2P_0/3P_0 - P_t]$ were found to be independent of the initial pressure (Table 5). A plot of $\log (3P_0 - P_t)$ *versus* time t gave a good straight line up to 60% decomposition. The variations of the rate coefficient with temperature are described in Table 6. The results given in Table 6 lead, by using the least squares procedure and 90% confidence limits, to the shown Arrhenius equation.

DL-Alanine ethyl ester hydrochloride

The theoretical stoichiometry for the elimination process of DL-alanine ethyl ester hydrochloride in the gas phase [reaction (6)] demands $P_f/P_0 = 4.0$. The average experimental P_f/P_0 values at 4 different temperatures and 10 half-lives was 4.1 (Table 1). Confirmation of stoichi-

ometry in Equation (6) was possible, when obtaining, up to 50% decomposition, good agreement between pressure measurements and the quantitative chromatographic analyses of ethylene (Table 2).

$$CH_3CH(NH_2 \cdot HCl)COOCH_2CH_3$$
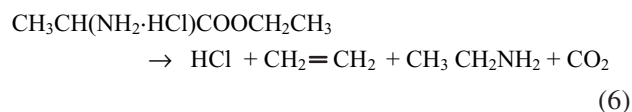$$\rightarrow HCl + CH_2{=}CH_2 + CH_3 CH_2NH_2 + CO_2 \quad (6)$$

Table 3 appears to indicate that reaction (6) is homogeneous, since no significant effect was obtained in the experiments when using both clean Pyrex and seasoned Pyrex vessels with a surface-to-volume ratio of 6.0 relative to that of the normal vessel. The effect of the free radical suppressor toluene is shown in Table 4. No induction period was observed. The rate coefficients are reproducible with a relative standard deviation not greater than ±5% at a given temperature.

The rate coefficient also calculated from $k_1 = -(2.303/t) \log [(4P_0 - P_t)/3P_0]$ was invariable of their initial pressure. When plotting first $\log (4P_0 - P)$ against time t a good straight line, up to 50% reaction, was obtained (Table 5). The temperature dependence of the rate coefficient and the corresponding Arrhenius equation is described in Table 6. (90% confidence coefficient from least-squares procedure).

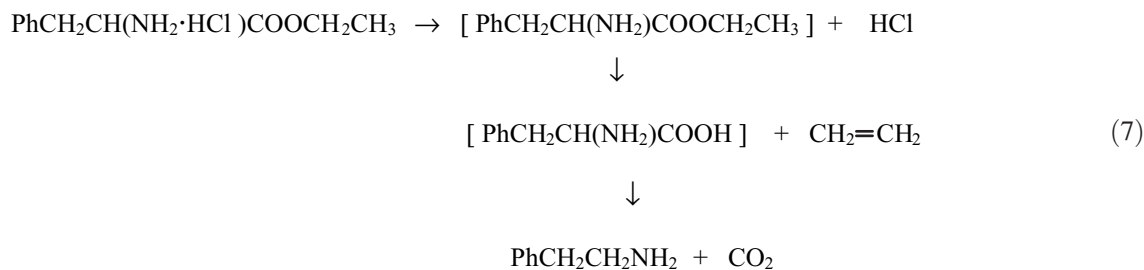### L-Phenylalanine ethyl ester hydrochloride

The gas phase elimination process of L-phenylalanine ethyl ester hydrochloride is described in reaction (7). The stoichiometry based on reaction (7) required that, for long reaction time $P_f/P_0 = 4.0$. The average experimental P_f/P_0 value at 4 different temperatures and 10 half-lives was 3.8 (Table 1). Verification of the above stoichiometry (7), up to 60% reaction, was possible when comparing that the corresponding ethylene gas produced is equivalent to pressure increase (Table 2). The elimination products,

Table 7. Comparative kinetic and thermodynamic parameters at 400°C

Z	$k_1 \times 10^4$ (sec^{-1})	Ea (kJ/mol)	log A (sec^{-1})	$\Delta S^{\neq}$ (J/mol K)	$\Delta H^{\neq}$ (kJ/mol)	$\Delta G^{\neq}$ (kJ/mol)
Glycine ethyl ester.HCl	3.02	203.7 ± 3.2	12.29 ± 0.24	−24.74	198.1	214.8
Sarcosine ethyl ester.HCl	8.97	215.0 ± 7.8	13.64 ± 0.60	1.10	209.4	208.7
DL-Alanine ethyl ester.HCl	8.94	200.2 ± 5.9	12.49 ± 0.46	−20.91	194.6	208.7
L-Phenylalanine ethyl ester.HCl	25.22	194.4 ± 1.1	12.49 ± 0.09	−20.92	191.3	205.4

within the range of rate determination were: phenethylamine, ethylene, carbon dioxide, and hydrogen chloride.

The rate coefficients were reproducible with a relative standard deviation less than ±5% at a given temperature.

$$PhCH_2CH(NH_2 \cdot HCl)COOCH_2CH_3 \rightarrow [PhCH_2CH(NH_2)COOCH_2CH_3] + HCl$$

$$\downarrow$$

$$[PhCH_2CH(NH_2)COOH] + CH_2{=}CH_2 \tag{7}$$

$$\downarrow$$

$$PhCH_2CH_2NH_2 + CO_2$$

The pyrolytic elimination of reaction (7) is homogeneous since no significant variations in the rates are observed when using both clean Pyrex and seasoned Pyrex vessels with a surface-to-volume ratio of 6.0 relative to that of the normal vessel, which is equal to 1.0 (Table 3). The pyrolysis experiments of this substrate were carried out in the presence of at least twice the amounts of the free radical inhibitor toluene in order to prevent any possible chain reaction. The effect of different proportions of toluene in the elimination process is shown in Table 4. No induction period was observed.

The rate coefficient of this elimination was found to be independent to initial pressures (Table 5), and the first-order rate was calculated from $k_1 = -(2.303/t) \log[(4P_0 - P_t)/3P_0]$. A plot of log $(4P_0 - P)$ against time (t) gave a good straight line up to 60% decomposition. The variation of the rate coefficient with temperature and the corresponding Arrhenius equation are given in Table 6 (90% confidence coefficient from the least-squares procedure).

Product formations and the kinetic and thermodynamic parameters given in Table 7 suggest a consecutive mechanism as described in reaction (8)

$$\tag{8}$$
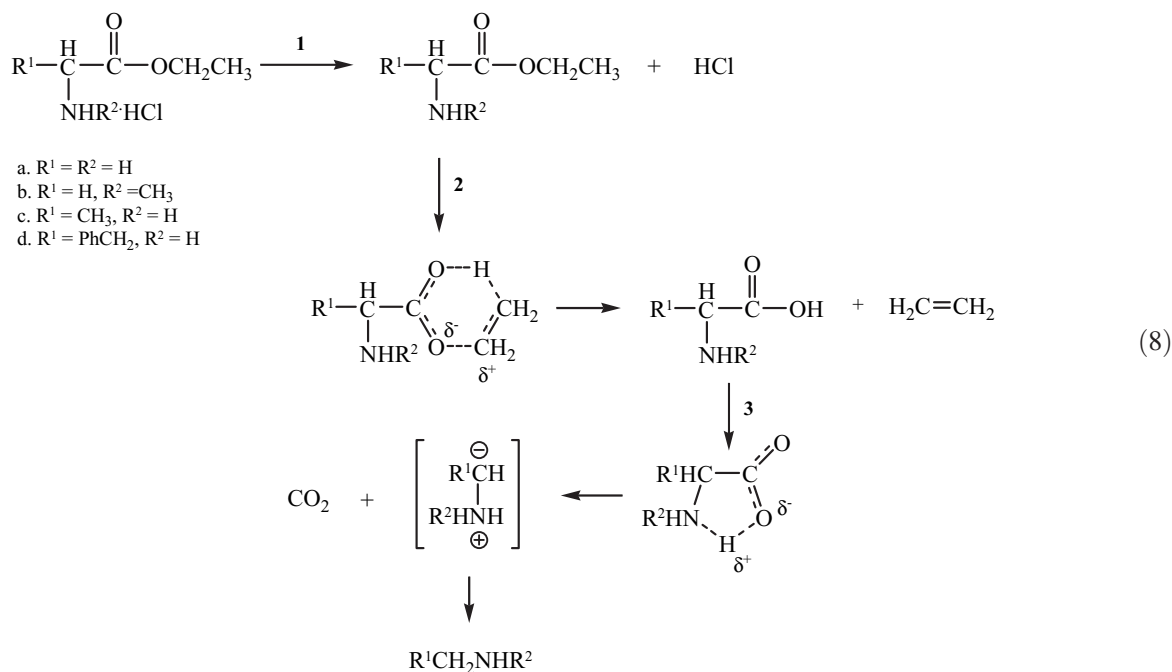
Step 1 is a fast process of dehydrochlorination. The ester intermediate proceeds through a slow determining **Step 2** for the formation of the corresponding α-amino acid and ethylene gas. The '*in situ*' unstable amino acid from **Step 2** rapidly decarboxylates to the corresponding amine (**Step 3**). Ethyl ester of sarcosine is the exception since only produces the corresponding amino acid. These results apparently support the consideration reported before[10–12] where α-amino acids decarboxylate to the corresponding amines. It is interesting to report that phenylalanine was found to decompose in a stainless steel reactor,[15] between 400–600°C from 4 sec to 1 min, with complex results.

The general concept that electron-withdrawing groups at the acid side of ethyl, isopropyl, and *tert*-butyl esters enhance the elimination rate, while electron-releasing groups reduce it has been described in a review on the structural effect on gas-phase reactivities.[16] However, the comparative rates of the gas phase reactivity of the ethyl esters of amino acid hydrochlorides listed in Table 7 seem to be contrary to the above-mentioned generalization. Steric accelerations appear to influence the process of decomposition. That is, the bigger the size or the more bulky is the substituent at the acyl side of the amino ester, the faster is the elimination rate of ethylene formation.

EXPERIMENTAL

Glycine ethyl ester hydrochloride (Aldrich), sarcosine ethyl ester hydrochloride (Aldrich), DL-alanine ethyl ester hydrochloride (Aldrich), and L-phenylalanine ester hydrochloride (Aldrich) of 99% purity were employed (GC-MS: Saturn 2000, Varian, with a DB-5MS capillary column 30 m × 0.25 mm. i.d., 0.25 μm film thickness). The products sarcosine, the hydrochloride salts of methylamine, ethylamine, and phenethylamine collected out of the reaction vessel were identified in a GC-MS (Saturn 2000, Varian) with a DB-5MS capillary column 30 m × 0.25 mm. i.d., 0.25 μm. The identification of ethylene and carbon dioxide were performed GC-MS (Saturn 2000, Varian) with megabore capillary column GS-Q 30 m, i.d. 0.53 mm with a TCD. The quantitative analysis of the product ethylene (Matheson) was carried out by using a Gas Chromatograph HP 5710A with a Porapak Q (80-100 mesh) column.

Kinetics

The kinetic experiments were performed in a static reaction system reported.[17–19] The rate coefficients were calculated from the pressure increase manometrically, or by the quantitative chromatographic analyses of ethylene product. The temperature was controlled by a Shinko DC-PS resistance thermometer controller and an Omega SSR280A45 solid-state relay, maintained ±0.2°C and measured with a calibrated Iron Constantan thermocouple. No temperature gradient was observed along the reaction vessel. The starting materials, dissolved in benzyl alcohol or acetic acid, were all injected directly into the reaction vessel with a syringe through a silicone rubber septum. The amount of substrate used for each reaction was ∼0.05–0.2 ml.

REFERENCES

1. Taylor R. The Chemistry of Functional Group. *Acid Derivatives*, Supplementary, vol. B, Saul Patai (ed). Wiley: London, 1979; Chapter 15.
2. Holbrook KA. The Chemistry of Acid Derivatives. *Vapor and Gas phase Reaction of Carboxylic Acids and their Derivatives*, vol. 2, Saul Patai (ed). Wiley: London, 1992; Chapter 12.
3. Al-Awadi NA, Kaul K, El-Dosouqui OME. *J. Phys. Org. Chem.* 2000; **13**: 499–504.
4. Safont VS, Moliner V, Andres J, Domingo LR. *J. Phys. Chem. A* 1997; **101**: 1859–1865.
5. Domingo LR, Andres J, Moliner V, Safont VS. *J. Am. Chem. Soc.* 1997; **119**: 6415–6422.
6. Domingo LR, Pitcher MT, Andres J, Moliner V, Safont VS, Chuchani G. *Chem. Phys. Lett.* 1997; **274**: 422–428.
7. Domingo LR, Pitcher MT, Safont V, Andres J, Chuchani G. *J. Phys. Chem. A.* 1999; **103**: 3935–3943.
8. Rotinov A, Chuchani G, Andres J, Domingo LR, Safont VS. *Chem. Phys.* 1999; **246**: 1–12.
9. Chuchani G, Domínguez RM, Rotinov A, Martín I. *J. Phys. Org. Chem.* 1999; **12**: 612–618.
10. Ensuncho A, Lafont J, Rotinov A, Domínguez RM, Herize A, Quijano J, Chuchani G. *Int. J. Chem. Kinet.* 2001; **33**: 465–471, and references cited therein.
11. Lafont J, Ensuncho A, Domínguez RM, Rotinov A, Herize A, Quijano J, Chuchani G. *J. Phys. Org. Chem.* 2003; **16**: 84–88.
12. Dominguez RM, Tosta M, Chuchani G. *J. Phys. Org. Chem.* 2003; **16**: 869–874.
13. Al-Awadi SA, Abdallah MR, Hasan MA, Al-Awadi NA. *Tetrahedron* 2004; **60**: 3045–3049.
14. Rosas F, Monsalbe A, Tosta M, Herize A, Dominguez RM, Brusco D, Chuchani G. *Int. J. Chem. Kinet.* 2005; **37**: 383–389.
15. Shulman GP, Simmonds PG. *Chem. Commun.* 1968, 1040–1042.
16. Chuchani G, Mishima M, Notario R, Abboud JL. Structural Effect on Gas-Phase Reactivities. *Advances in Quantitative Structure-Property Relationship*, vol. 2, Charton M, Charton BI (eds). JAI Press, Inc.: Stamford, Connecticut, USA, 1999.
17. Maccoll A. *J. Chem. Soc.* 1955: 965–973.
18. Swinbourne ES. *Aust. J. Chem.* 1958; **11**: 314–330.
19. Dominguez RM, Herize A, Rotinov A, Alvarez-Aular A, Visbal G, Chuchani G. *J. Phys. Org Chem.* 2004: **17**: 399–408.